PB86-144623

Modeling Transport by Convective Clouds for Regional Air Pollution Models

Research Triangle Inst.
Research Triangle Park, NC

Prepared for

Environmental Protection Agency
Research Triangle Park, NC

Dec 85

U.S. Department of Commerce
National Technical Information Service
NTIS

PB86-144623

EPA/600/D-86/002
December 1985

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EPA Contract 68-02-4059

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RESEARCH TRIANGLE PARK, NC 27711

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TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA/600/D-86/002	2.
3. RECIPIENT'S ACCESSION NO. PB86 144623/AS	
4. TITLE AND SUBTITLE MODELING TRANSPORT BY CONVECTIVE CLOUDS FOR REGIONAL AIR POLLUTION MODELS	5. REPORT DATE December 1985
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Vukovich, F.M. and Ching, J.K.S.	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Research Triangle Institute RTP, NC. 27709	10. PROGRAM ELEMENT NO. CCVN1A/01-3094 (FY-86)
	11. CONTRACT/GRANT NO. (C) 68-02-4059
12. SPONSORING AGENCY NAME AND ADDRESS Atmospheric Science Research Laboratory-RTP,NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED
	14. SPONSORING AGENCY CODE EPA/600/09
15. SUPPLEMENTARY NOTES	

16. ABSTRACT

A model is developed to account for regional scale vertical transport of pollutants from the mixed layer to the overlying free troposphere by an ensemble of non-precipitating cumulus convective clouds. The model determines acceptable cloud classes for given atmospheric state represented by the moist static energy distribution. The cloud classes are defined by dry entrainment rate, cloud depth and convective cloud amounts. The clouds are of course driven by regional scale heat and moisture convergence. Empirical data was collected and used to formulate a closure scheme to obtain the necessary cloud parameters. A statistical model which predicts the vertical distribution of cloud amount from cloud base was developed. The vertical variation of cloud amounts depends on the distribution of clouds having different depths.

17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO ES
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

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1. INTRODUCTION

Cumulus clouds have their roots within the mixed layer. Warm, moist air in convective eddies cools in rising thermals. If saturation is reached while in the updraft stages, the water vapor condenses and the parcel gains additional buoyancy with the release of latent heat of condensation. The parcel will rise to greater altitudes until the additional buoyancy is spent. The noncloud air in the free troposphere will subside in a complex manner to maintain mass balance. Rising air within the cloud contains a variety of pollutants from the mixed layer in the cloud water phase; as a result, chemical transformations can occur. When the cloud with this pollutant burden dissipates, the transport and diffusion of the pollutants are then constrained by the free tropospheric flow regime, and subsequently the pollutants undergo horizontal displacements in directions differing from that in the underlying mixed layer. These pollutants can be transported great distances. They may eventually reenter the mixed layer through precipitating systems or by reentrainment through mixing from below. They may also remain in the free troposphere where they eventually disperse. The complexities of transport and conversion processes associated with cumulus convection is indeed a significant problem.

Because of the importance of this process, it must be accounted for in regional-scale air quality modeling in order to properly assess and predict air quality on that scale. In an effort to properly understand acid deposition on a regional scale, the United States Environmental Protection Agency is sponsoring a program to develop a Regional Acid Deposition Model (RADM), which is being developed at the National Center for Atmospheric Research (NCAR). As a part of the development program, a module is being created that will be integrated into the RADM and will account for transport by an ensemble of nonprecipitating, subgrid-scale, cumulus clouds.

2. CLOUD FLUX MODEL

The cloud flux model will calculate the vertical flux of an air pollution species due to an ensemble of nonprecipitating, subgrid-scale, air mass convective clouds. This model will be integrated into the RADM and will serve to establish the effects of cloud venting for the RADM. The basic algorithm that is being used to describe the cloud flux is the Ritter model (Ritter and Stedman, 1985). The Ritter model determines the acceptable cloud classes for a given atmospheric state. The atmospheric state is represented by the moist static energy distribution, and the cloud classes are defined by a dry air entrainment rate, cloud depth, and convective cloud amount. The entrainment rate is assigned to a particular cloud size, which is represented by the cloud depth. The greatest entrainment rate is assigned to those clouds having the least depth, and the smallest entrainment rate, to clouds having the greatest depth. It is assumed that a cloud grows to be a large cloud because it has a small value of entrainment.

The primary forcing function that produces the cloud in the Ritter model is heat and moisture convergence. Radiative cooling is also included as a forcing term, but it is not as important as the heat and moisture convergence. Given the acceptable cloud classes for an atmospheric state, the cloud characterization based on cloud amount and cloud depth, and the magnitude of the forcing functions, the Ritter model will compute the cloud base mass flux from which the flux vertical velocity can be determined.

Ritter initially developed this model for a data assimilation mode. Radiosonde data were used to define the moist static energy distribution and satellite data, and to characterize the clouds in terms of depth, number density, and cloud amount. This closure is unacceptable for NCAR's RADM since satellite data are not available from the RADM. Therefore, a new closure procedure had to be determined.

The new closure procedure for the Ritter model used basic meteorological variables (e.g., pressure, temperature, humidity, surface heat flux, etc.) to predict the needed parameters (e.g., convective cloud amount, cloud distribution parameters, etc.) since the basic variables were the only parameters available from the RADM. Various empirical models were developed using data obtained from the Venting Experiment (VENTEX) to estimate parameters. VENTEX took place outside of Lexington, Kentucky, from 9 July to 16 August 1984. Surface, upper-air, sodar, and aircraft measurements were made to characterize the lower atmosphere during cumulus convection and the cumulus clouds in terms of cloud amount, cloud depth, and cloud width. The measurement program was a joint effort by Battelle Pacific Northwest Laboratory, Argonne National Laboratory, and the Research Triangle Institute, and was sponsored by the United States Environmental Protection Agency.

Figure 1 is a flow diagram for the cloud flux model and will be used to describe the preprocessing that must be done and the parameterization that was developed for closure of the Ritter model. There are a number of basic tests which must be performed and a number of parameters which must be established before the Ritter model can be used to calculate the cloud mass flux. The first step is to determine whether dry convection is occurring in the boundary layer; i.e., tests to determine whether the surface heat flux is positive. If dry convection is occurring, then it must be determined whether the atmospheric conditions will support moist convection. This is determined by testing the relative height of the entrainment zone (Deardorff et al., 1980) compared to the relative height of the lifting condensation level (LCL) zone (Wilde and Stull, 1984). If the bottom of the LCL zone intersects the top of the entrainment zone, moist convection is presumed to exist.

After it has been determined that moist convection exists, values for various parameters must be established in order to execute the Ritter model. One of the most important parameters is the convective cloud amount. As previously indicated, Ritter originally used satellite data to determine the cloud amount. RADM does not provide satellite data. The RADM is a predictive model, and it is not possible to use satellite observations in the predictive mode because of inconsistencies that will arise between observations and predictions. The RADM does provide basic meteorological parameters (pressure, temperature, humidity, etc.) and such parameters as the surface heat flux, the height of the top of the boundary layer, the height of the LCL, and the dew point depression as a function of pressure. These parameters, and those which can be computed from these parameters, are the only parameters available for use in estimating the convective cloud amount.

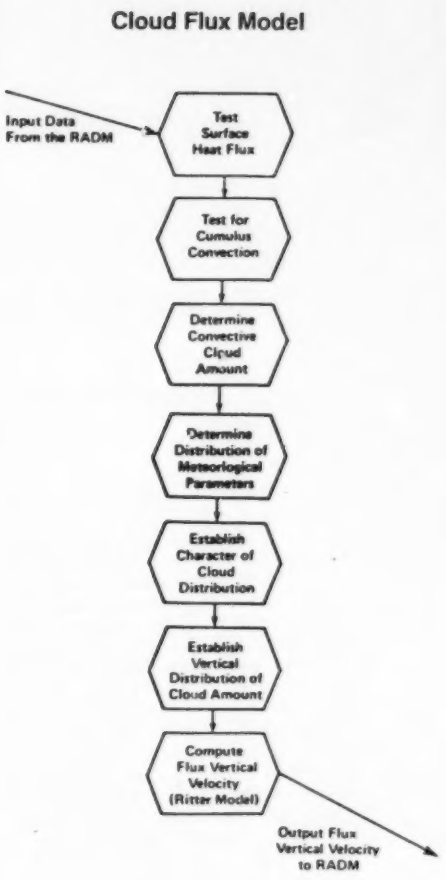
Cloud Flux Model
Input Data From the RADM
Test Surface Heat Flux
Test for Cumulus Convection
Determine Convective Cloud Amount
Determine Distribution of Meteorological Parameters
Establish Character of Cloud Distribution
Establish Vertical Distribution of Cloud Amount
Compute Flux Vertical Velocity (Ritter Model)
Output Flux Vertical Velocity to RADM

Fig. 1. Flow diagram of cloud flux model.

A statistical model which predicts the cloud amount at cloud base was developed for the cloud flux model using observations of cloud amount and basic meteorological parameters from the VENTEX program. The regression model estimated the convective cloud amount as the function of the dew point depression at the surface and at the top of the boundary layer, the surface heat flux and the time rate of change of the surface heat flux, the height of the LCL, the free convective scaling velocity, surface temperature and the height of the top of the boundary layer; i.e.,

$$\alpha_o = C_o + C_1 T_s + C_2 \Delta T_s + C_3 \Delta T_{PBL} + C_4 Z_{LCL} + C_5 w_* + C_6 \Delta H + C_7 \Delta Z + C_8 H^2 + C_9 H^3 + C_{10} \Delta H^2 + C_{11} \Delta H^3 . \quad (1)$$

where α_o is the convective cloud amount at cloud base, the C's are the model parameters, T_s is the surface temperature, ΔT_s is the dew-point depression at the surface, ΔT_{PBL} is the dew-point depression at the top of the PBL, Z_{LCL} is the height of the lifting condensation level, w_* is the convective scaling velocity, H is the surface heat flux, ΔH is the 15-minute change in the

surface heat flux, and ΔZ is the difference in height between the top of the PBL and the lifting condensation level. Comparisons of the observed cloud amount to the predicted cloud amount using Equation (1) yielded a correlation coefficient of 0.84 (Figure 2).

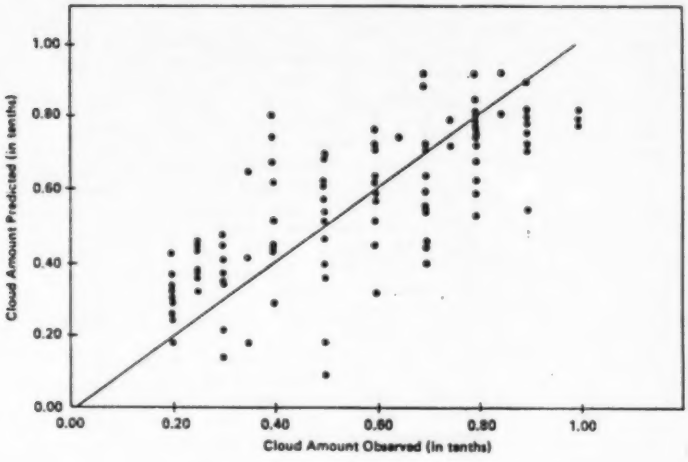

Fig. 2. Comparison of observed cloud amount to predicted cloud amount using regression model. The linear line represents a correlation of 1.0.

After the convective cloud amount at cloud base was established, the vertical variation of the convective cloud amount needed to be determined. A vertical variation of the cloud amount existed because the cloud amount was established by the distribution of clouds having different depths. The first step in establishing the vertical distribution of the convective cloud amount was to establish the characteristics of the cloud population for the given cloud base cloud amount. Two distinct cloud distributions were allowed in the model. These distributions were a function of the moisture characteristics above the PBL. If the atmosphere was dry above the PBL, it was assumed that the convective clouds have shallow, uniform depths and the convective cloud amount was independent of height through the cloud layer. If it was moist above the PBL, it was assumed that the cloud size distribution was lognormal (Hozumi et al., 1982; López, 1977; Planck, 1969; Hill, 1974). The determination of the state of the atmosphere above the PBL was based on the comparison of the dew-point depression above the PBL to an empirically determined limiting value; i.e., if the dew-point depression was less than or equal to 7.0°C at a level that was 500 m greater than the height of the top of the PBL, it was considered to be moist above the PBL. Based on the assumption that the cloud distribution was lognormal, the convective cloud amount has the following relationship with the integrated cloud size distribution;

$$\alpha(z) = \alpha_o \, [\exp(-bD) - \exp(-bD^*)] \; ; \qquad (2)$$

where α is the convective cloud amount at height z, b is the slope parameter for the lognormal distribution, D is the cloud width, α_o is in percent, and D^* is the width of that cloud whose depth is equal to 1500 m. It has been suggested by Planck (1969) and Hill (1974) that clouds whose depths are greater than 1500 m are precipitating clouds. Therefore, in order to account for only nonprecipitating clouds, the precipitating clouds were excluded by limiting the cloud depths. Equation (2) provides that exclusion.

Convective cloud population studies that are presented in the literature have indicated that a formal relationship can be derived between the cloud width and cloud depth with reasonable accuracy. Observations from the VENTEX program were used to determine this relationship for the closure of the Ritter model.

Figure 3 is a plot of the observed cloud depth and cloud width from VENTEX, and a plot of a second-order curve which was used to model the relationship. The correlation coefficient for this model was 0.86.

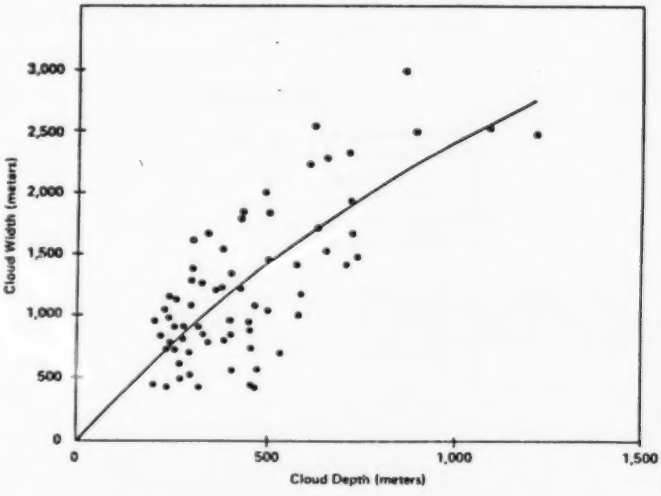

Fig. 3. Observed cloud depth versus observed cloud width, and a plot of the second order curve fitted to the observation and used to parameterize a relationship between these two variables.

Hozumi et al. (1982) has shown that the slope function, b, in a lognormal distribution, can be represented as an exponential function of convective cloud amount. The VENTEX data and GOES satellite data that were collected during VENTEX, were used to derive the relationship for this closure procedure. The substantive relationship was

$$b = 1.078 \exp(-1.05 \, \alpha_o) \; . \qquad (3)$$

The constants in Equation (3) are different from those derived by Hozumi et al. Hozumi et al. used AMTEX 74 and 75 data to derive their relationship, and those data were collected in tropical cumulus. Differences in relationships derived from mid-latitude and tropical cumulus are to be expected. Equation (2) combined with Equation (3) and the model relating cloud width and cloud depth provided the vertical distribution of the convective cloud amount under the condition that the region above the PBL was moist.

The models and the procedures outlined above provided the major parameters needed for closure of the Ritter model and for calculating the convective cloud mass flux. The vertical distribution of pressure, temperature, and humidity, which are required to derive the distribution of the moist static energy for the environment, are basic input parameters readily available from the RADM.

The algorithm for the cloud flux model has been completed and some initial runs have been performed. However, complete validation of the model has not been accomplished. Validation of the model will begin during the next phase of this research project. It is expected that at least one more, and possibly two more, generations of this model will be accomplished before a completely validated model has been developed.

Acknowledgment

The research was funded by the United States Environmental Protection Agency under Contract No. 68-02-4059. The material in this paper does not necessarily reflect the views or the policies of the United States Environmental Protection Agency.

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